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DAIRY FARM MANAGEMENT WHEN NUTRIENT RUNOFF AND CLIMATE EMISSIONS COUNT

SANNA LÖTJÖNEN, ESA TEMMES, AND MARKKU OLLIKAINEN

We provide a theoretical framework and detailed bioeconomic simulations to examine privately and socially optimal dairy farm management in the presence of nutrient runoff and greenhouse gas emissions. Dairy farms produce milk by choosing herd size, diet, fertilization and land allocation between crops, as well as (discrete) manure storage and spreading technologies and the number of milking seasons. We show analytically that a critical radius emerges for the choice of land use between silage and cereal cultivation and fertilizer types (mineral and manure). Both privately and socially optimal manure application rates decrease with application distance. We characterize the optimal climate and water policy instruments for dairy farming. A detailed bioeconomic simulation model links farm management decisions with their impacts on climate and water quality. We numerically solve the social and private optima and the features of optimal climate and water policy instruments. We show that using only climate instruments provides considerable water co-benefits, and in the same vein, the use of water quality instruments provides considerable climate co-benefits. Climate policies lead to a reduction in herd size, as measures relating to manure management and spreading are relatively inefficient at reducing climate emissions. There is much more leeway for adapting to water policies than to climate policies, because dairy farms have multiple measures to reduce their nutrient loads.

Key words: Critical radius, dairy management, greenhouse gas emissions, nutrient runoff, optimal diet, spatial pattern of manure application.

JEL codes: Q12, Q15, Q18, Q52.

Agricultural dairy production is currently receiving much attention in terms of environmental policy. Methane emissions from animal husbandry and other greenhouse gases increase global warming. Nutrient loads from

dairy production are considerable in many regions, such as the Baltic Sea and the Chesapeake Bay. Designing effective environmental policies requires a good understanding of the specific nature of animal husbandry. Dairy production differs in many important ways from crop production. Instead of a land parcel, the primary production unit is the production animal, and arable farmland mostly has a supporting role in dairy production, serving mainly as a source of animal feed. Another key difference is the production and use of manure. Manure is concurrently a costly byproduct and a valuable fertilizer source for crops. Costly manure transportation impacts decisions concerning its use.

Livestock accounts for approximately 80% of the non-carbon dioxide (CO₂) emissions from agriculture, and the greatest share of this stems from ruminants (Havlik et al. 2014). Methane (CH₄) emissions from enteric fermentation and manure management are the main

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sources of greenhouse gas (GHG) emissions from dairy production (Gerber et al. 2013). Manure storage and spreading cause nitrous oxide (N_2O) emissions. In addition, nitrogen (N) is volatilized as ammonium (NH_3) during manure storage and spreading. Volatilized N reduces the amount of N available for crops in manure. Measures to reduce GHG emissions in dairy production are relatively scarce. Diet slightly impacts GHG emissions, as does the spreading technology. By far, the most effective short-term measure to reduce emissions is to reduce the number of productive animals while increasing the productivity of milking cows in the long term. Feed production is also a significant source of emissions (Gerber et al. 2013).

Animal husbandry produces nutrient loads from many sources. Poorly designed and managed manure storage systems may leak or spill over. Manure spreading onto fields is another source of nutrient runoff; the amount of runoff depends on the amount of manure used per hectare and the spreading technology (in addition to exogenous properties of field parcels). Diet choice impacts the amount and nutrient content of manure and, thereby, not only crop yields but also runoff. In addition to improving manure storage facilities, the dairy farmer can reduce nutrient runoff by measures similar to those used in crop production (such as reducing fertilization, using buffer strips and catch crops, see Lichtenberg 2002; Shortle and Horan 2001; Lichtenberg 1989; Lankoski and Ollikainen 2003).

The objective of this paper is to examine the climate policy toward dairy farming when society considers nutrient loading to be a co-benefit or an independent policy objective and vice versa for nutrient policy. We provide a formal analysis of the privately and socially optimal dairy management in the presence of either nutrient runoff or GHG emissions or both. Farmers are assumed to target nitrogen application in cereal and silage production, because in most cases nitrogen is the limiting factor for crop growth. Furthermore, nitrogen provides a common source of both GHG emissions and nutrient runoff through the continuous choices of diet, manure application and land allocation, as well as discrete technology choices. Focusing on both global and regional pollutants, we compare the private spatial pattern of the use of manure and mineral fertilizers to the social optimum. Drawing on this comparison, we derive the first-best and second-best policy instruments that shift the private solution to the socially optimal one.

To facilitate comparison of results with previous theoretical work (Schnitkey and Miranda 1993; Innes 2000) focusing on steady-state use of phosphorus instead of nitrogen, we also examine how phosphorus policies relate to climate policies. Special focus on phosphorus also helps to link our analysis to the recent discussions on finding solutions to the excess manure produced by livestock farms. Excess manure is a main source of high phosphorus loads in many countries and notably in the US (Kaplan, Johansson and Peters 2004; Huang, Magleby and Christensen 2005). The root cause of the phosphorus problem lies in the fact that manure has an excessive phosphorus content relative to nitrogen with regard to crop needs. Finding crop fields outside of livestock farms for application of excess manure is difficult, and developing other solutions, such as separation of nutrients, has been challenging, especially for manure from dairy farms (Innes 2000; Kaplan, Johansson and Peters 2004; Huang, Magleby and Christensen 2005; Iho, Parker and Zilberman 2012). Nevertheless, manure export has been steadily increasing in the US and elsewhere. For instance, in Nebraska, 36% of survey respondents exported livestock manure (Glewen and Koelsch 2001), and in Tennessee, 37% of survey respondents exported poultry litter (Jensen et al. 2010). Additionally, companies are starting to use more livestock manure to generate energy (BHSL Hydro 2019).

In our model, the farm manager maximizes revenues from milk production by choosing herd size and diet, fertilization and land allocation between crops, the number of milking seasons, and the technologies implemented for manure storage and spreading. Diet choice lies at the heart of the model. Changes in diet impact milk production (per-animal profits), methane emissions from enteric fermentation, manure excretion and nutrient composition, fertilizer application, and land allocation between crops. We provide general results characterizing the impacts of prices, costs, and taxes on the optimal management of dairy farms. This leads to general hypotheses concerning the impacts of exogenous variables on dairy farm management decisions and thereby GHG emissions and nutrient loads. To examine the hypotheses numerically and provide further insights, especially for the discrete technology choices, we develop a detailed bioeconomic simulation model and link all relevant climate and water quality impacts of farm management decisions to the model. We numerically solve the social and

private optima, and describe the features of optimal climate and water policies.

Our work relates to previous literature as follows. Starting with climate emissions, there are no theoretical treatments of the subject, but several whole-farm models numerically calculate dairy farm GHG emissions, for example DairySim, FarmGHG, SIMS_{DAIRY}, and FarmSim (Schils et al. 2007). These models differ from one another, for instance, in terms of precision and system boundaries. Many of these models also account for nutrient flows but are mainly designed for simulating GHG emissions. Many studies also consider climate change mitigation measures, such as increasing productivity or reducing animal numbers, through simulations (Garnett 2009). Lengers and Britz (2012) use a detailed biodynamic DAIRYDYN model to analyze GHG emission abatement and conclude that policies targeting GHG emissions should be based on indicators rather than on actual emissions. Baerenklau, Nergis, and Schwabe (2008) and Key and Kaplan (2007) modeled ammonia emissions from manure storage and application, which is also done in our model. Arndt et al. (2018) showed that altering manure management practices, especially by reducing solids in slurry, could mitigate cattle-related CH₄ emissions. Considering both nutrient runoff and GHG emissions, Schils et al. (2006, 2007) concluded that historically in the Netherlands and in simulation models, more efficient N management in dairy farming has also led to reduced GHG emissions.

Turning to water quality issues, Kaplan, Johansson, and Peters (2004); Yap et al. (2004); Key and Kaplan (2007) and Baerenklau, Nergis, and Schwabe (2008) provide numerical simulations and examine either farmers' choices or impacts of selected manure policies. The most commonly examined policy instruments are restrictions on fertilization intensity. Depending on the paper, farmers adjusted to policies by changing fertilization and herd size, and by making (discrete) technological decisions concerning manure storage and application. Yap et al. (2004); Helin (2014); and Bosch, Wolfe, and Knowlton (2006) allowed the farmer to also adjust the diet of the animals and suggested that diet alteration is an important means of adjusting to policies.

With two notable exceptions (Schnitkey and Miranda 1993; Innes 2000), theoretical treatments of dairy farm management in the presence of nutrient loading are absent, and so are studies on socially optimal production choices. Schnitkey and Miranda (1993) show the existence of a

critical radius that defines an outer limit for manure application in the steady state. Mineral fertilizers are applied beyond this radius because they are not sensitive to transportation distance. They also show that phosphorus intensity is higher in all fields where manure is used relative to that of mineral fertilizers. Innes (2000) uses a more general and regional model and confirms Schnitkey and Miranda's result on the critical radius and finds that a private optimum produces too many animals in too many facilities. Our paper examines analytically whether these features show up when the focus is on nitrogen instead of phosphorus under the hypothesis that a similar pattern emerges for nitrogen application.

Our paper contributes to the literature in many ways. First, unlike previous literature, we provide a comprehensive theoretical model of dairy farming and for the first time in the literature derive how exogenous variables and policy instruments impact private dairy management and thereby both climate and water quality impacts. Second, we analytically develop key features of optimal climate and water policies that address the spatial aspects of fertilizer and crop choice. Third, we focus on the coherence between water and climate policies by asking how water policy instruments promote climate targets and vice versa.

The rest of our paper is organized as follows. We develop a theoretical framework and provide a formal analysis of privately and socially optimal dairy production. Then, we present the simulation model. The next section gathers results from numerical simulations and presents sensitivity and policy analyses. The last section provides conclusions.

Dairy Farm Model

This section describes the dairy farm model. We first develop an analytical model focusing on both socially and privately optimal choices and government policy instruments. We then present the detailed implementation of the numerical simulation model.

Basic Model Set-up

Consider a dairy farm with H lactating cows. Their diet consists of two components: concentrate feeds and silage. The farmer decides on the quantity of the concentrate feed, and the animals have free access to silage. The quantity of concentrate feed, denoted by v , impacts the voluntary silage intake so that the total intake

becomes a function of concentrate feeding $\gamma(v)$ ($\gamma_v > 0$). The composition and total quantity of consumed feedstuff affects the milk yield, manure excretion, and manure nutrient content. As total intake and feed composition are fully determined by the quantity of the concentrate feed used, we denote the milk production function by $g(v)$ ($g_v > 0$), the manure production function by $w(v)$ ($w_v > 0$), the manure N content by $\theta^N(v)$, and the manure P content by $\theta^P(v)$ ($\theta_v^P > 0$ and $\theta_v^N < 0$, with the feeds used in the simulations). We assume a fixed share of calves and heifers per dairy cow, which is determined endogenously by the optimal number of milking seasons (i.e. lactations).

We assume that the farmer produces all silage on farm, as silage markets are typically local and unreliable due to high transportation costs. Silage therefore has no conventional input price; rather, its profitability is defined by production and opportunity costs. Concentrates, in contrast, have a market price of p^v , and the produced milk is sold at a price of p^M . Animal upkeep costs and profits from exported animals are assumed to be constant per milking cow and are denoted by φ . Function $i(H)$ describes the annual capital costs of investments given herd size, for example, production facilities, machinery, and animal shelters. Thus, we express the total direct net profit from milk production as

$$(1) \quad \pi_1 = [p^M g(v) - v p^v - \varphi] H - i(H)$$

The farmer manages a given size of farmland, denoted by A . We assume that the spatial distribution of the land follows a continuous density function, $q(r)$, where r marks the distance from the center of the farm. If R represents the distance to the furthest point of the farm, then land distribution can be expressed as

$$(2) \quad A = \int_0^R q(r) dr$$

All facilities are located at the farm center by assumption. At every point on the farmland, the farmer chooses whether to produce silage or cereals and then chooses the appropriate amounts for manure and mineral fertilizer applications. We assume that the land is homogenous with respect to all other properties except distance. Because silage has relatively high transportation costs per unit

compared to cereals, silage production will be allocated in areas close to the farm center. Furthermore, given that manure has significantly higher transportation costs than mineral fertilizers, manure is applied to parcels close to the production facilities. As the relative profitability of both silage production and manure application decreases monotonically with distance, unique distances exist, marking the outer limits for silage production and manure application, which need not coincide. We denote the critical radius for manure application by r^m and that for silage production by r^s .

Nitrogen is assumed to limit crop growth. Thus, we employ response functions with N as the only decision variable. $f^s(N)$ denotes the yield response function for silage, and $f^c(N)$ denotes the same for cereals. The total N fertilization at a given point (distance) is defined by the amount of applied manure and mineral fertilizer ($m(r)$ and $l(r)$, respectively), and their N content ($\theta^N(v)$ and ϵ^N , respectively). Mineral fertilizer has a market price of $p^l(r)$, and due to its compact nature, its application cost is minor. Manure, in contrast, is a free byproduct of milk production and has high transportation and application costs, denoted by $a(r)$, which can be given different values depending on the discrete choice of spreading technology. We assume that this function increases linearly with r . The farm has the possibility of exporting excess manure at increasing costs to nearby areas, and we denote this transport cost with $C(r)$.

A processing cost term is introduced for both crops, including costs from harvesting, storage, and other associated expenses. For silage, hauling causes a significant share of the processing costs, making the costs dependent on the distance to the parcel in question. Distance-related costs for cereals are considered insignificantly small. Thus, the per-unit silage processing costs are a function of distance, $h^s(r)$, and the corresponding cost term for cereals is constant, h^c . Produced silage has no off-farm market value and cannot be exported, whereas cereals are exported at a unit price of p^c .

We combine the above components and express the profits from farmland cultivation as a sum of silage and cereal production subtracted by the manure export cost:

A comparison of equations (1) and (3) shows that the farmer does not make separate decisions on milk production and cultivation because the two production lines are linked together.

$$\begin{aligned}
 \pi_2 = & \int_0^{r^s} [-h^s(r)f^s(\varepsilon^N l(r) + \theta^N(v)m(r)) - p^l(r)l(r) - a(r)m(r)] q(r) dr \\
 (3) \quad & + \int_{r^s}^R [[p^c - h^c]f^c(\varepsilon^N l(r) + \theta^N(v)m(r)) - p^l(r)l(r) - a(r)m(r)] \\
 & q(r) dr - C(r) \left[w(v)H - \int_0^R m(r)q(r) dr \right].
 \end{aligned}$$

Dairy production causes environmental impacts for which society accounts. Here, we focus on damages from GHG emissions and N and P runoff. Nutrient runoff depends on the applied amounts of nutrients, the manure spreading technology, and the cultivated crop. In the numerical simulations, we focus on injection and broadcast spreading. Additionally, we assume that the propensity for runoff is identical for both fertilizer inputs. Pointwise nutrient loads from silage and cereal cultivation, x^s and x^c , respectively, are separated as the propensity to runoff differs between the two crops. Reflecting the ratio in which algae use nutrients in their growth, we express N and P runoff as nitrogen equivalents, \hat{N} , where P is transformed into \hat{N} using the Redfield-ratio ς (Kiirikki et al. 2003). Thus, runoff as a function of fertilization can be given by $\int_0^{r^s} x^s(\hat{N}(r))q(r)dr$ and $\int_{r^s}^R x^c(\hat{N}(r))q(r)dr$ for silage and cereals, respectively, where $\hat{N}(m(r), l(r), v) = N + \varsigma P = \theta^N(v)m(r) + \varepsilon^N l(r) + \varsigma(\theta^P(v)m(r) + \varepsilon^P l(r))$, that is, the amount of N in manure and in mineral fertilizers and the amount of P transformed into \hat{N} in manure and mineral fertilizers.

The pointwise nutrient load damages from cultivating silage and cereals are presented in equation (4), where d^w denotes the (constant) marginal water damage:

$$(4) \quad d^w \left[\int_0^{r^s} x^s(\hat{N}(r))q(r)dr + \int_{r^s}^R x^c(\hat{N}(r))q(r)dr \right]$$

The description of damages is simple in equation (4), as we focus on a single dairy farm. Nutrient runoff damages include both nitrogen and phosphorus as nitrogen equivalents, and

both nutrients are assumed to cause eutrophication. This is the case in semiclosed sea areas with brackish waters, for example, in the Chesapeake Bay, the Baltic Sea, and the Black Sea. Shifting the analysis to a landscape level would require accounting for the transfer of nutrients toward waterways and the impacts of aggregate loads on water quality. Focusing on the landscape level would modify, but not fundamentally change, the results of the farm-level analysis.

Cattle are the main source of GHG emissions from dairy farming because they emit CH₄. Methane emissions are created by enteric fermentation and are diet dependent. Thus, expressed as CO₂-equivalents (CO₂-eq.), the emissions per cow can be given as $e^c(v)$ ($e_v^c > 0$). Manure storages are a source of N₂O and CH₄ emissions. CO₂-eq. emissions from storages (open or covered) per cow can be defined as $e^{st}(v) = \rho w(v)$ where ρ is a coefficient, and we postulate that $e_v^{st} < 0$. The sign is negative due to reductions in manure N content and volatile solids excretion, which dominate the effect of increased manure excretion.

The cultivation process itself is a source of GHG emissions. Conventional broadcast spreading technologies cause ammonia (NH₃) emissions and indirect emissions of N₂O, which is a strong GHG. An injection technology is an alternative that effectively eliminates NH₃ emissions but causes direct N₂O emissions. The CO₂-eq. emissions from manure spreading are given as $e^{sp}(r) = \sigma m(r)$, where m refers to one cubic meter of manure spread on land at distance r , and σ is a coefficient (depending on the spreading technology). Finally, autonomous GHG emissions from soil and emissions from machinery per hectare are denoted by s^s and s^c for silage

and cereal, respectively, and emissions from the manufacturing of mineral fertilizers by $\delta l(r)$.

We denote GHG emissions from silage and cereal cultivation by $\int_0^{r^s} (g^s(m(r), l(r)))q(r)dr$ and by $\int_{r^s}^R (g^c(m(r), l(r)))q(r)dr$, respectively, where g^s and g^c refer to pointwise GHG emissions, $(\sigma m(r) + \delta l(r) + s^s)$ and $(\sigma m(r) + \delta l(r) + s^c)$. Denoting the constant marginal climate damage by d^c gives total climate damage as follows:

$$(5) \quad d^c \left[E(v)H + \int_0^{r^s} g^s(m(r), l(r))q(r)dr + \int_{r^s}^R g^c(m(r), l(r))q(r)dr \right]$$

where $E(v) = e^c(v) + e^{st}(v)$ is the climate emissions from cattle and manure storage.¹

Society maximizes social welfare from dairy production (6) subject to two constraints: silage used in the diet and manure application cannot exceed the amounts actually produced (7):

$$(6) \quad \max_{v, H, r^s, m(r), l(r)} \Pi^W = [p^M g(v) - v p^v - \varphi - d^c E(v)]H - i(H) - C(r) \left[w(v)H - \int_0^R m(r)q(r)dr \right] + \int_0^{r^s} [-h^s(r)f^s(\varepsilon^N l(r) + \theta^N(v)m(r)) - p^l(r)l(r) - a(r)m(r) - d^w x^s(m(r), l(r), v) - d^c g^s(m(r), l(r))]q(r)dr + \int_{r^s}^R [p^c - h^c]f^c(\varepsilon^N l(r) + \theta^N(v)m(r)) - p^l(r)l(r) - a(r)m(r) - d^w x^c(m(r), l(r), v) - d^c g^c(m(r), l(r))]q(r)dr$$

$$(7) \quad s.t. \quad \begin{cases} \int_0^{r^s} [f^s(\varepsilon^N l(r) + \theta^N(v)m(r))]q(r)dr - [\gamma(v) - v]H \geq 0 \\ w(v)H - \int_0^R m(r)q(r)dr \geq 0. \end{cases}$$

¹ In summary, the negative environmental impacts considered in the model include (1) GHGs from cow enteric fermentation (CH_4), $e^c(v)$, and from manure storage (N_2O , CH_4), $e^{st}(v) = \rho w(v)$ (giving $E(v) = e^c(v) + e^{st}(v)$ as the cow-specific emissions), (2) GHGs from manure spreading (N_2O , NH_3), $e^p(r) = \sigma m(r)$, from silage and cereals (soil and machinery; CO_2 , N_2O , CH_4), s^s and s^c , respectively, and from mineral fertilizer manufacture (CO_2), $\delta l(r)$ (giving $g^s = \sigma m(r) + \delta l(r) + s^s$ and $g^c = \sigma m(r) + \delta l(r) + s^c$), and (3) nutrient runoff from silage and cereal production (N , P), $x^s(\dot{\text{N}}(r))$ and $x^c(\dot{\text{N}}(r))$, respectively.

We express the Lagrangian function of the constrained maximization problem in a way that facilitates a simple and clear presentation of the economic choices and describe the derivation of the Lagrangian function and the explicit equations characterizing the optimum in the online supplementary appendix 2

$$(8) \quad L^W(v, H, r^s, l(r), m(r), \lambda_1, \lambda_2) = [\Omega H - d^c E H - i(H)] + [\Pi^s - D^s + \Pi^c - D^c]$$

Equation (8) decomposes the dairy farm management decisions to those relating to the net revenue from milk production (Ω) and silage and cereal cultivation (Π^s and Π^c , respectively) under the two constraints and environmental impacts (d^c denoting the damage from GHG emissions from animals [E], and D^s and D^c denoting joint climate and water externalities from silage and cereal cultivation-related processes, respectively). The model framework

is illustrated in figure A1 in the online supplementary appendix 1.

Analytics

We use equation (8) to express socially optimal dairy management in a simple and intuitive way. Setting environmental damage

functions equal to zero produces the privately optimal choice. The exact formulas are compiled and reported in the online supplementary appendix 2. The formulas indicate that via the choice of diet and the constraints, all decision variables impact all parts of the Lagrangian function (equations A1–A9). The decision variables of the model are herd size H , concentrate feed intake v , manure $m(r)$ and mineral fertilizer application $l(r)$ at distance r , and the critical radius for silage cultivation r^s .

Optimal herd size. The social and private herd size decisions are determined at the point where the marginal revenue from the last head added to the herd equals its marginal costs, as equations (9a) for the society and (9b) for the private farmer suggest:

$$(9a) \quad \Omega - d^c E - i'(H) = 0,$$

$$(9b) \quad \Omega - i'(H) = 0.$$

Society accounts for the climate impacts from enteric fermentation and manure; thus, the socially optimal herd size is smaller than the private herd size. As equations (A3a) and (A6) reveal, land allocation and fertilization decisions affect the direct net revenue per cow. Depending on the attractiveness of manure as a fertilizer input, land allocation and fertilization decision may either increase or decrease the herd size in both optima.

Optimal diet. The optimal diet is determined by the choice of concentrate feed and the properties of intake function, which then determines the required silage use. The optimality conditions are as follows:

$$(10a) \quad (\Omega_v - d^c E_v)H + \Pi_v^s - D_v^s + \Pi_v^c - D_v^c = 0$$

and

$$(10b) \quad \Omega_v H + \Pi_v^s + \Pi_v^c = 0$$

The derivatives show that concentrate feeding impacts at the margin not only the value of concentrate productivity in milk production and associated feeding costs but also generates positive stock effects for both silage and manure, thereby increasing marginally profits from silage and cereals. This creates an incentive to increase concentrate feeding beyond the level supported by milk production alone,

as the private optimality condition (10b) suggests. This impact is, however, reduced at the social optimum, which accounts for climate and water externalities caused by higher amounts of concentrate feeding.

Optimal land allocation. Arable land must be allocated between cereals and silage. Despite having no market value, the shadow price of silage reflects the internal value of produced silage and is, therefore, a key component in the profit comparisons. Producing silage removes farmland from cereal production. The optimal land allocation requires the comparison of profits and damages from each crop at each location while accounting for the requirement of silage production. As silage harvesting costs increase with distance, but cereal harvesting costs are constant, the competitiveness of silage production against cereals declines monotonically with distance. The critical radius r^s indicates the distance after which producing cereals becomes more profitable and is defined as follows:

$$(11a) \quad \Pi^s(r^s) - D^s(r^s) + \Pi^c(r^s) - D^c(r^s) = 0$$

and

$$(11b) \quad \Pi^s(r^s) - \Pi^c(r^s) = 0$$

Land allocation at the social optimum depends on how prone silage and cereals are to both climate and water damage, and how intensively these crops are fertilized. Silage typically causes significantly smaller leaching and soil GHG emissions than cereals, thus increasing its attractiveness in cultivation. The critical radius in the private optimum neglects environmental externalities, leading to a higher land area allocated to cereal cultivation. Note that the crops do not have identical fertilization rates; equations (11a)-(11b) are based on the optimal fertilization of both crops.

Optimal fertilization: Manure and mineral fertilizer. The optimal fertilizer application can be solved pointwise: for both fertilizer types and each location, the optimal fertilizer rate is determined by the equality of the value of the marginal product to the marginal social costs of the fertilizer comprising the input costs and the sum of the marginal water and climate damages. While mineral fertilizer has a constant unit cost (price), with the cost of application slightly increasing with distance, manure

has an increasing transport cost over locations. The critical radius for manure application r^m defines the distance where it is optimal to switch from manure to mineral fertilizer application. The determination of r^m requires some calculation (see online supplementary appendix 2), but the switching point can be expressed in a rather simple form:

$$(12a) \quad \frac{a - C + D^i(m, r^m)}{\theta^N} = \frac{p^l + D^i(l, r^m)}{\varepsilon^N}$$

and

$$(12b) \quad \frac{a - C}{\theta^N} = \frac{p^l}{\varepsilon^N}$$

where a denotes manure transportation and application costs, C denotes the manure export cost, p^l represents the mineral fertilizer price, θ^N and ε^N represent the manure and mineral fertilizer N contents, respectively, and D^i , with $i = s, c$, denotes the joint climate and water externalities from silage and cereal cultivation, respectively. The private solution equals the costs of manure and mineral fertilizer at location r and is independent of crop choice between silage and cereals (12b). The social solution depends on the crop type due to the different environmental damages associated with silage and cereals (12a), which increase the total social costs of applying both manure and mineral fertilizers. As the social solution is not independent of crop choice, two radii appear. In practice, two radii can coexist only if the radius is greater for cereals than for silage. In this case, manure application will continue after the change of crops, despite the farmer having switched to mineral fertilization within silage parcels. In the numerical simulations, we find that for both cases, the radius is so long that one radius actually turns out to be empirically relevant. Given that both fertilizer forms are perfect substitutes in crop production, fertilizers are not used jointly; the cheapest type is always chosen. Therefore, close to the farm center, manure will be applied exclusively until mineral fertilizer becomes less costly at a certain distance. Beyond this range, only mineral fertilizer is applied, and at the critical radius, the optimal N application rate is equal for both fertilizers. Thus, we conclude that relative to mineral fertilizer application, the N application rate is always higher on parcels under manure fertilization, except at the point of indifference. As a result, under an identical damage function,

the closest parcels contribute to more severe runoff damage than the furthest fields.

Our first key theoretical results on the differences between private and social choices can be summarized as follows. The private producer has too many animals, uses too much concentrate feed and too much fertilizer, and allocates too much land for cereal production compared to the social optimum, leading to nutrient loads and GHG emissions that are too high. From a theoretical perspective, the most striking difference relates to fertilization, as unlike the social optimum, the private critical radius for manure application is independent of crop choice. This shows that none of the variables are crop specific (see equations [12b] and [A9d]) because a private farmer ignores environmental loads. Intensified fertilization increases the manure scarcity and its shadow price, and shortens the critical radius of manure application. Nevertheless, given the increasing manure hauling cost at location r , the spatial pattern of a monotonically declining manure application rate is found both in the private and in the social optimum. This result is new in the literature. Both Innes (2000) and Schnitkey and Miranda (1993) focused on the difference between manure and mineral fertilizer intensities, assuming implicitly that it would be socially preferable to fertilize evenly on all parcels.

Finally, equations (1)–(12a and 12b) characterize the continuous choices of dairy farming subject to any discrete choice of technologies and the number of milking seasons. Technological choices include manure storage with or without a cover and manure spreading via broadcast or injection. The combination that provides the highest private profits or social welfare is chosen.

Both socially and privately optimal choices are characterized as a simultaneous solution of herd size, diet, fertilization, and land allocation, all depending on exogenous variables. The comparative statics of the private solution are presented in table 1 (see details of the derivation in the online supplementary material 1). In deriving the comparative statics, we assume a constant manure N content, an interior solution for manure application (the latter constraint in equation (7) is ignored) and that silage is fertilized solely with manure and cereals solely with mineral fertilizer. As the parameters are solved endogenously and simultaneously, parameters other than the one in focus have a strong impact on the results. Next, we provide a short interpretation of the results.

Table 1. Results of the Comparative Statics for the Private Optimum

	H	v	$l(r)$	$m(r)$	r^s
p^M	+	+	0	+	+
p^v	—	—	0	—	—
φ	—	—	0	—	—
$a(r)$	—	+	0	—	—
$C(r)$	—	—	0	+	+
p^c	—	+	+	+	—
$p^l(r)$	+	—	—	—	+

*The sign is determined under the parameter values used in private optimization; otherwise, the sign is ambiguous.

The economic interpretation of the comparative statics results concerning herd size and the use of concentrate feed is straightforward: when profitability of milk production increases due to change in any exogenous variable (milk or concentrate feed price or constant cost per dairy cow), both the herd size and use of concentrate feed increase. What then happens to manure application and land allocation between silage and cereals is more complicated and depends on two opposing effects. The higher herd size tends to increase the land area allocated to silage, but this is counter affected by the higher use of concentrate feed tending to decrease the need for silage. Here, changes in herd size dominate, and the silage area increases with herd size. Similar interpretation can be provided for manure application: both higher herd size and concentrate feed use increase the amount of manure tending to increase per hectare fertilization, whereas increased silage area tends to decrease the amount of manure applied per hectare. The overall effect is an increase in per-hectare manure application.

In addition, prices determining revenue from crop production indirectly impact milk production. A higher crop (fertilizer) price decreases (increases) herd size and increases (decreases) the use of concentrate feed and manure application. Mineral fertilizer intensity is independent of variables directly impacting milk production (due to the simplifying assumption) and depends positively on crop prices and negatively on fertilizer prices.

The role of the manure hauling cost is interesting. An increase in application costs decreases herd size to reduce the amount of manure produced but increases concentrate feed use, which enhances manure excretion. The impact on per hectare manure use and land allocation is negative, as lowered herd size tends to decrease silage area and

increased manure application cost tends to decrease manure application. In contrast, higher costs of manure export tend to increase manure application on a farm's own fields to reduce the need for exporting and to allocate more land to silage. A subsidy on manure export would reduce manure applications on a farm's own fields. A similar effect can be achieved with administrative policy instruments; for example, the US Nutrient Management Plan regulates the spreading of manure on livestock farms' own fields, but if the manure is exported to a crop farm, these regulations no longer apply (Iho, Parker, and Zilberman 2012). Based on equation (A9d), an increase in the mineral fertilizer price or manure export cost lengthens the critical radius for manure application, whereas an increase in the manure hauling cost shortens the critical radius ($\frac{dr^m}{dp^m} > 0$, $\frac{dr^m}{da} < 0$ and $\frac{dr^m}{dc} > 0$).

From society's perspective, the private optimum entails excessive GHG emissions and nutrient runoff. The policy challenge is to reduce two different types of externalities: global climate emissions and regional water quality damages. The first-best policy design is to levy instruments targeting both GHG emissions and nutrient runoff. Alternatively, given that GHG emissions and runoff are produced somewhat jointly, society may design a second-best policy targeting either GHG emissions only or nutrient runoff only. We examine both alternatives here. We consider a Pigouvian policy consisting of an optimal carbon tax on GHG emissions (τ^G) and a (second-best) nutrient tax on fertilization (τ_s^N, τ_c^N) (instead of a loading tax, as cultivation causes nonpoint source pollution).

Taxes are derived by introducing them to the private profit maximization problem and solving for tax rates that make the socially and privately optimal solutions identical (including technology choice). Solving the taxes yields the following:

$$(13a) \quad \tau^G = d^c, \forall r$$

$$(13b) \quad m: \tau_j^N(r) = d^w x_N^j \left(\hat{N}(m^*(r), v^*) \right) (\theta^N(v^*) + \zeta \theta^P(v^*))$$

and

$$(13c) \quad l: \tau_j^N = d^w x_N^j \left(\hat{N}(l^*(r) \right) (\varepsilon^N + \zeta \varepsilon^P), \text{ with } j = s, c.$$

Drawing on equations (13a) – (13c), the second set of our theoretical results is as follows. The optimal carbon tax (13a) is uniform and equal to the marginal climate damage reflecting society's valuation and levied on all sources of GHG emissions. In contrast, the nitrogen tax is a second-best tax reflecting the marginal propensity of nitrogen equivalent fertilization to estimated runoff valued by the marginal water quality damage (Shortle and Dunn 1986).

The tax on manure (13b) is differentiated in each location because, due to transport cost, fertilization by manure differs between all locations (Lankoski and Ollikainen 2003; Ervola, Lankoski and Ollikainen 2012; Lötjönen and Ollikainen 2017), and the tax on mineral fertilizer (13c) is also slightly differentiated. This spatial difference in manure and mineral fertilizer application and crops suggests that policies targeting loading from crop production farms and dairy farms, respectively, should also be differentiated. Should society address GHG emissions only and levy the climate tax on all emissions, equation (13a) would still hold, but addressing nutrient loading only would result in a higher tax rate for the nutrient tax due to the missing impact of climate tax on fertilization intensity. We acknowledge that using differentiated instruments would entail transaction costs when implemented. Therefore, it is interesting to focus on some uniform taxes instead. One possibility is to use a uniform tax on nutrients and set a separate instrument on CH₄ emissions from animals. Drawing on the comparative statics results, we can postulate that the former works like an increase in the price of mineral fertilizer or like an upward shift in manure spreading costs. For the latter, animal-based tax impacts like an increase in the net costs per cow. We examine the size of the impacts and the potential welfare loss in numerical simulations.

Model Implementation

To further illustrate the properties and examine the overall impacts of the model, we next present a numerical application. The data are tailored to Finnish agriculture, but with case-specific data, the model could also be applied to other countries. The simulation model used closely follows the analytical model, except that the continuous spatial distribution of farmland of the theory is replaced with

discretely distributed parcels of a given acreage in the simulations (60 ha in total in 6-ha field parcels at 0.5 km intervals), and we add pasture land (see details below). Although the total field area is around the average value in Finland (Niskanen and Lehtonen 2014), the distances of field parcels from the farm center are chosen to illustrate the effect of distance. The calculations are performed with Mathematica 11.2. For details on the data used, see the online supplementary appendix 3.

The total intake function for dairy cows is from Huhtanen et al. (2008). Functions for manure excretion and nutrient content are derived using data from Nennich et al. (2005), with typical feed nutrient values, and scaled to match Finnish estimates. For a concentrate feed intake of 15.9–16.1 kg/day, the manure nitrogen content rounds up to 1.7 kg N/m³, and the phosphorus content rounds up to 0.60 kg P/m³. The milk yield function is based on Lehtonen (2017). Dairy cows are assumed to have three to six milking seasons (i.e. lactations) before they are slaughtered. This number determines the required number of calves and heifers for replacement to keep animal numbers constant. Additional milking seasons would reduce the required number of young animals and thereby also GHG emissions, but as a downside, milk yield is reduced after three milking seasons. Dry cows are not accounted for separately. The milking season of dairy cows is 300 days/year, and otherwise functions for intake and manure excretion are the same for the entire year. Intake and manure excretion (Finlex 2014) of heifers and calves are assumed to be constant.

Manure is stored as a slurry. Part of the nitrogen in the slurry is lost as volatilized NH₃ during manure storage and after manure application. Manure storage is either covered (floating cover, 4% of N is lost during storage) or uncovered (10% of the N is volatilized). After application to fields, 9% to 40% of the slurry nitrogen content is lost via volatilization depending on the spreading technology (injection or broadcast, respectively). Data on nitrogen volatilization are from Grönroos (2014). Quadratic nitrogen yield responses used for barley and silage are based on Lehtonen (2017).

A quadratic cost function is used to describe the annual per-cow capital cost of investments in dairy farming and is calibrated to limit the optimal number of animals to approximately 60 dairy cows (one milking robot). We allow the per dairy cow net profit term φ to include the profit from exported animals and the

upkeep costs from calves and heifers. Manure excretion of heifers and calves is added to the total quantity of manure produced. Note that no fixed costs are included in the model. The distance-related costs of silage processing and manure application are estimated using Finnish data on contractor fees (Palva 2015). The unit cost of manure export is assumed to equal the hauling cost for the distance of 1 km further than the furthest parcel of the modeled dairy farm, that is, we assume the recipient pays for the application costs.

The exponential nitrogen runoff function is based on Simmelsgaard (1998). The phosphorus runoff function is a logarithmic function, based on Ekholm et al. (2005) and Uusitalo and Aura (2005), including both soluble and bioavailable particulate P. The unit damage of nitrogen runoff (9 €/kg N runoff) is based on an estimate by Gren and Folmer (2003) concerning the marginal willingness-to-pay for reduced nitrogen runoff in the Baltic Sea region. Phosphorus unit damage is derived from the previous studies using the Redfield ratio of 7.2, which allows the expression of phosphorus runoff in nitrogen equivalents when accounting for the optimal nutrient ratio for phytoplankton growth in the Baltic Sea (Kiirikki et al. 2003). GHG emission calculations for dairy production and manure are mainly based on the Finnish GHG Inventory Report (Statistics Finland 2016). Values for soil emissions are based on Heikkinen et al. (2013) and emissions from cultivation measures on Ervola et al. (2018). To express different GHGs as CO₂ equivalents, we use the common approach of global warming potential of 100 years (GWP₁₀₀), instead of giving less emphasis on non-CO₂ emissions, as some researchers have suggested, regarding them as systemic emissions in contrast to fossil-based CO₂ emissions (Allen et al. 2016). The climate damage value (50 €/t CO₂-eq.) is chosen based on Tol (2011). The marginal climate damage from GHG emissions is constant as it is a global emission. Although a regional effluent, marginal damage from nutrient runoff is also considered constant. Field parcels as runoff sources within one farm are geographically so close together that we can assume an equal proximity to watercourses and thus an equal eutrophication potential. If the model was extended to cover multiple farms, varying damage depending on the location and transport of nutrients would become relevant.

Manure spreading technologies affect nutrient runoff and GHG emissions. Due to missing

information and mixed effects, each spreading technology is assumed to have the same impact on N runoff (Rotz 2004; Uusi-Kämpä 2010; Uusi-Kämpä and Mattila 2010) and on direct N₂O emissions (Webb et al. 2010). The effect on phosphorus runoff is based on Uusi-Kämpä and Heinonen-Tanski (2008). Impacts on the amount of volatilized NH₃, and thus indirect N₂O emissions, are accounted for based on Grönroos (2014) as explained above.

In addition to the field parcels allocated to silage or barley cultivation, the farm has a separate area for pasture (42 ha in total is assumed). We assume a part-time grazing period of four months and, thus, an unchanged diet throughout the year despite pasturage. The grazing period and stocking density used are the average values for Finland. Part of the manure produced is excreted on the pasture (i.e. less manure for storage and spreading), and the area is also fertilized with mineral fertilizer. Cultivation costs and GHG emissions from the pasture are assumed to be the same as those for silage. The extra pasture area (the maximum 42 ha minus the stocking density multiplied by the herd size) is used to cultivate barley with the same mineral fertilization as in the private optimum. Market prices, costs, nutrient runoff, and GHG emissions for the barley are the same as above.

Simulations

We next present the results from the simulations. We derive separately the optimal decisions for each technology combination and choose the one yielding the highest profit or welfare (only the optimal solution is presented). Simulations are performed for a Finnish Baltic Sea case described above. Sensitivity analysis allows us to test the robustness of the results while changing the values of exogenous parameters (detailed results are shown in the online supplementary material 2). Finally, we study climate and water policy instruments and discuss the role of phosphorus.

Results

Private and Social Optima: The Baseline

We collect the baseline simulation results for private and social optima in table 2. The social optimum is presented for three alternative cases, where society accounts for (a) GHG

emissions only (climate policy scenario), (b) nutrient runoff only (water policy scenario), and (c) both GHG emissions and nutrient runoff (joint policy scenario). In each case, social welfare includes both types of damage, even if they are not accounted for in the optimization.

Comparing private and social optima, we first observe that herd size differs considerably; the joint policy scenario has nine animals less than the private optimum. In each case, there is a maximum of two barley parcels out of the ten field parcels. Allocating all parcels to silage cultivation is optimal for the water and joint policy scenarios. In the social optima silage is preferred to barley as the propensity to nutrient runoff and soil GHG emissions is higher for cereals.

Optimal concentrate feeding is intensive. In fact, in every case, the feeding level is higher than the milk yield maximizing value (15.65 kg DM/day). This is what the theory suggested: the farmer values the increase in manure stock to the extent that he trades off some of his milk revenues for valuable fertilizer in cultivation. The result is, however, highly dependent on relative market prices. For example, decreased milk, barley, or mineral fertilizer price results in reduced concentrate feeding below the milk yield maximizing level (see detailed sensitivity analysis results in the online supplementary material 2). The result also implies that concentrate feed use depends on herd size compared to the amount of farmland available, again underlining the

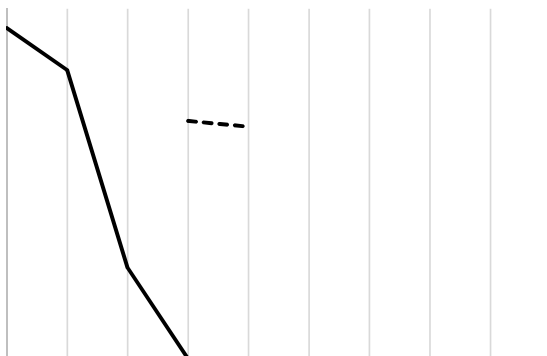
interdependency of the decisions regarding milk production and land use. This is confirmed in the sensitivity analysis, where a higher stocking density and increased cultivation area both result in a lower concentrate intake level for the water and joint policy scenarios. Finally, note that despite the changes in diet appearing quite small at first glance, a 1-kg change in silage feeding in the daily ration of a single cow amounts to an annual quantity of over 21,000 kg with the baseline herd size, equaling a yield of approximately 5 ha.

Optimal manure storage and spreading technologies are identical for all cases. The difference in profits or social welfare between no cover and floating cover is quite small if the spreading technology does not change. Fertilization is based either on manure or mineral fertilizer. Figure 1 illustrates the spatial pattern of manure and mineral fertilizer application. Optimal nitrogen application is solved for each discrete distance (0.5, 1,..., 5 km), and these points are combined to provide a clear illustration. Figure 1 confirms the pattern we derived analytically in the previous chapter. The manure application rate is higher on the parcels closest to the farm center and decreases monotonically when moving further away from the farm center.

Furthermore, as the critical radius marks the point where the mineral fertilizer and manure application rates would be equal, the nitrogen application rate of fields receiving manure is always higher than the nitrogen application rate of parcels under mineral

Table 2. Optimal Simulation Results Under the Baseline

	Private	Climate policy	Water policy	Joint policy
Herd size, dairy cows	62	56	59	53
Barley parcels (out of 10 parcels)	2	2	0	0
Milk, kg/animal/year	9,213	9,213	9,215	9,214
Milk in total, kg/farm/year	571,206	515,928	543,685	488,342
Milking seasons	3	3	3	3
Concentrates, kg DM/animal/day	16.09	16.12	15.70	15.91
Silage, kg DM/animal/day	5.91	5.89	6.21	6.05
Manure in storage, m ³ /animal/year	24.56	24.56	24.51	24.53
Manure in total, m ³ /farm/year	1,531	1,376	1,457	1,291
Manure exported, m ³ /year	0	0	0	0
Manure storage cover (no/floating)	floating	floating	floating	floating
Manure spreading (broadcast/injection)	broadcast	broadcast	broadcast	broadcast
Total nutrient runoff, kg N-eq./year	3,352	3,150	2,947	2,784
Total GHG emissions, kg CO ₂ -eq./year	502,374	463,997	459,641	418,994
Private profits, €/farm/year	87,019	86,050	85,456	82,974
Runoff damages, €/farm/year	30,166	28,346	26,520	25,058
Climate damages, €/farm/year	25,119	23,200	22,982	20,950
Social welfare, €/farm/year	31,735	34,504	35,954	36,966



fertilization. Note that the notch in fertilization pattern marks the outer range of silage production in the private optimum, whereas barley requires less fertilization. Comparing the socially optimal fertilization patterns, we observe that when moving from accounting for only one type of damage to both damages, the overall fertilization level decreases.

Turning next to environmental impacts, the socially optimal solutions feature 8–17% smaller climate damages and 6–17% smaller runoff damages relative to the private optimum; these damages are the smallest when both externalities are accounted for. The water policy scenario leads to lower GHG emissions than the climate policy scenario. This is explained by two factors. First, under nutrient policies, the farmer has a larger set of management options available: it now pays to reduce fertilizer application and allocate land for silage (and less for cereal crops). A higher silage area and lower use of mineral fertilizer both contribute to a reduction in GHG emissions. For the climate policy scenario, netting manure management and diet impact GHG emissions only negligibly. Additionally, soil emissions are rather independent of management decisions. Second, the size of the marginal climate damage versus water damage matters. We also studied the effect of varying climate and water damage on the results (see the online supplementary material 2). Lowering water damage (to 7.2 €/kgNe) or increasing climate damage (to 65€/tCO₂e) affects such that water policies alone do not decrease GHG emissions more than climate

policies alone. This finding is discussed more in the concluding remarks.

To shed further light on the difficulty of reducing GHG emissions, we provide table 3, which highlights how the key sources of GHG emissions differ in the four cases of table 2. Clearly, the greatest reduction possibility when only climate damage counts is found by reducing the number of animals. This action eliminates a total of 32,096 kg CO₂e emissions from enteric fermentation, manure storage and pasture, whereas other measures eliminate only 6,280 kg CO₂e, more than five times less. When only nutrient loading counts, the reduction from enteric fermentation, manure storage and pasture is 13,480 kg CO₂e, and from other measures, the reduction is 29,253 kg CO₂e. Here, changes in land allocation and fertilization play a much larger role.

In summary, our baseline results reproduce the key insights from the theoretical analysis: the private farmer uses too much the polluting inputs (herd size, diet, land allocation, fertilizer) and therefore causes too much pollution relative to the social optimum.

The baseline results imply that reducing herd size is an effective albeit expensive means to reduce GHG emissions. Thus, we next look at how nutrient runoff and GHG emissions would change if the farmer switches the production line from mixed dairy-crop production to pure crop production (no milk production, manure, or pasture land). To keep the analysis simple, we assume that revenue from selling the animals out covers the adjustment costs to crop production. The results are illustrated in table 4.

